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Solar Energy System Performance Evaluation

EL CAMINO REAL
ELEMENTARY SCHOOL
Irvine, California
October, 1978 through March, 1979

U.S. Department of Energy

National Solar Heating and
Cooling Demonstration Program

National Solar Data Program

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SOLAR ENERGY SYSTEM PERFORMANCE EVALUATION

IRVINE SCHOOL
(EL CAMINO REAL ELEMENTARY SCHOOL)
IRVINE, CALIFORNIA

OCTOBER 1978 THROUGH MARCH 1979

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NATIONAL SOLAR DATA PROGRAM REPORTS

Reports prepared for the National Solar Data Program are numbered under a specific format. For example, this report for the El Camino Real School project site is designated as SOLAR/2021-79/14. The elements of this designation are explained in the following illustration.

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- Report Type Designation:

  This number identifies the type of report, e.g.,

  - Monthly Performance Reports are designated by the numbers 01 (for January) through 12 (for December).

  - Solar Energy System Performance Evaluations are designated by the number 14.

  - Solar Project Descriptions are designated by the number 50.

  - Solar Project Cost Reports are designated by the number 60.

These reports are disseminated through the U. S. Department of Energy, Technical Information Center, P. O. Box 62, Oak Ridge, Tennessee 37830.

1. FOREWORD

The National Program for Solar Heating and Cooling is being conducted by the Department of Energy under the Solar Heating and Cooling Demonstration Act of 1974. The overall goal of this activity is to accelerate the establishment of a viable solar energy industry and to stimulate its growth in order to achieve a substantial reduction in non-renewable energy resource consumption through widespread applications of solar heating and cooling technology.

Information gathered through the Demonstration Program is disseminated in a series of site-specific reports. These reports are issued as appropriate and may include such topics as:

- Solar Project Description
- Design/Construction Report
- Project Costs
- Maintenance and Reliability
- Operational Experience
- Monthly Performance
- System Performance Evaluation

The International Business Machines Corporation is contributing to the overall goal of the Demonstration Act by monitoring, analyzing, and reporting the thermal performance of solar energy systems through analysis of measurements obtained by the National Solar Data Program.

The System Performance Evaluation Report is a product of the National Solar Data Program. Reports are issued periodically to document the results of analysis of specific solar energy system operational performance. This report includes system description, operational characteristics and capabilities, and an evaluation of actual versus expected performance. The Monthly Performance Report, which is the basis for the System Performance Evaluation Report, is published on a regular basis. Each parameter

presented in these reports as characteristic of system performance represents over 8,000 discrete measurements obtained each month by the National Solar Data Network.

All reports issued by the National Solar Data Program for the El Camino Real Elementary School solar energy system are listed in Section 6, References.

The El Camino Real Elementary School (hereafter referred to as the Irvine School) is in the Irvine Unified School District of Irvine, California.

This Solar Energy System Performance Evaluation Report presents the results of a thermal performance analysis of the Irvine School solar energy system. The analysis covers operation of the system from October 1978 through March 1979. The Irvine School solar energy system provides space heating and cooling to a school building located in the town of Irvine, in Central Orange County, California. A more detailed system description is contained in Section 3. Analysis of the system thermal performance was accomplished using a system energy balance technique described in Section 4. Section 2 presents a summary of the results and conclusions obtained while Section 5 presents a detailed assessment of the system thermal performance.

Acknowledgements are extended to those individuals involved in the operation of the Irvine School solar energy system. Their insight and cooperation in the resolution of various on-site problems during the reporting period were invaluable.

2. SUMMARY AND CONCLUSIONS

This System Performance Evaluation report provides an operational summary of the solar energy system installed at the Irvine School, an elementary school building located in Central Orange County, southeast of Los Angeles, California. This analysis is conducted by evaluation of measured system performance and by comparison of measured weather data with long-term average climatic conditions. The performance of major subsystems is also presented.

The measurement data were collected [References 7-12]* by the National Solar Data Network (NSDN) [1] for the period September 1978 through March 1979. System performance data are provided through the NSDN via an IBM-developed Central Data Processing System (CDPS) [2]. The CDPS supports the collection and analysis of solar data acquired from instrumented systems located throughout the country. This data is processed daily and summarized into monthly performance reports. These monthly reports form a common basis for system evaluation and are the source of the performance data used in this report.

Features of this report include: a system description, a review of actual system performance during the report period, analysis of performance based on evaluation of meteorological load and operational conditions, and an overall discussion of results.

Monthly values of average daily insolation and average outdoor ambient temperature measured at the Irvine School site are presented in Table 5.1-1. Also presented in the table are the long-term, average monthly values for these climatic parameters.

The Irvine School solar energy system is an example of an alternative energy retrofit onto an existing building. The Irvine School is a 41,000 square foot building in Irvine, California. The school operates on a trimester system which results in relatively constant use throughout the year. Additionally, the location in Orange County, California, provides a very moderate climate without extremely large heating and cooling loads.

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*Numbers in brackets designate References found in Section 6.

Prior to the installation of the solar energy equipment, space heating and cooling at the school was accomplished by a gas fired boiler. Hot water from the boiler was circulated through the air handling units to perform space heating, and through two 100 ton Arkla absorption chillers for space cooling. An existing Heating, Ventilation, and Air Conditioning (HVAC) system such as this allowed for relatively easy retrofitting of a solar energy system.

Several types of collector systems were examined before the Owens-Illinois evacuated tube design was selected. It appeared to offer the best performance and reliability, and the high operating temperature appeared to be compatible with the existing system. Thermal analyses were performed during design, and the results indicated that in this climate, with the typical school operating schedule, the energy demands in the building are in phase with the solar energy availability. The result is that a storage system for collected solar energy is not cost effective, and therefore was not included in the design. The solar energy system is connected to the existing hot water system through a heat exchanger. Utilization of high temperature collectors, such as the Owens-Illinois evacuated tube design, without a thermal storage system to absorb excess collected energy introduces the dangerous possiblity of overheating during low load periods. To avoid this occurrence, a water-to-air heat exchanger was added to the collection loop as an excess heat rejection mechanism.

The solar system was designed to satisfy 55 percent of the total annual space heating and cooling loads. This is accomplished with a total of 5,000 square feet of effective collector area. There are 18 banks of collector modules on the roof of the school, with ten modules per bank. A module consists of 24 evacuated glass collector tubes and the associated plumbing.

The retrofit construction was completed in March 1978 and system operation began in June. Typical startup problems prevented normal system operation until July and August. Similar problems with the data acquisition

system and the solar energy system controls prevented the continuous acquisition of data until the middle of September. The first monthly performance report for the Irvine School was published for the month of September, but data was only available for the latter half of the month. Since this data and the calculated monthly performance factors were not complete, they are inconsistent when compared to the following months' values, and will not be included in this Performance Evaluation Report. Instead, the data presented in this report will begin with the first full month of recorded data, October 1978.

In general, performance of the solar energy system at Irvine School has been relatively poor. During the months of August and September, personnel at the site determined collector efficiencies of 48 percent and solar fractions of 55 to 60 percent [13]. The following six months have produced collector efficiencies averaging 40 percent, and an average solar fraction of 12 percent. The only plausible explanation for this apparent reduction in capability is recurring problems with the control system and lack of solar energy due to the shorter daylight hours.

Several control system anomalies or malfunctions and hardware problems have been discovered in the various subsystems at the Irvine School. These directly impact the solar energy system performance and reduce the overall operating efficiency. Due to their importance, they will be discussed in some detail in the following paragraphs.

The collector subsystems may operate in either the collector protection mode or the solar collection mode. Problems with the control system for both modes have been observed. The collector protection mode is designed to prevent thermal shock to the collectors before and after operation of the main collector pumps. This is accomplished by circulation of water by auxiliary pumps at a relatively low (approximately one-tenth of collection flow rate) flow rate. A time clock initiates this mode in the morning before sunrise and terminates it in the evening after sunset.

A separate study performed on this site by Science Applications, Inc. [14] indicated that the auxiliary pumps were operating continuously during the night. Subsequent communication with personnel at the site verified this condition, and indicated the cause of the problem to be a malfunctioning freeze control thermostat which was out of calibration by approximately 19°F. This incorrect operation resulted in a waste of significant electrical energy, but more importantly, a loss of thermal energy by radiation from the collectors at night. The heat exchanger subsystem at Irvine School is designed to act as a thermal diode by allowing energy to flow from the collector subsystem to the space heating and cooling subsystems but not from these subsystems to the collector subsystem. However, manlfunctions in the control system allow thermal energy to readily flow into the collector loop, and this, in combination with the malfunctions in the auxiliary collector pump control, allow the rejection of the large amounts of thermal energy at night. Observations have shown the magnitude of this energy rejection to be larger than one-half of that collected during the day.

Circulation through the main collector loop, when in the solar collection mode, is designed to be controlled by a temperature differential across the heat exchanger. To prevent the possible loss of thermal energy by radiation, the main collector pumps should not operate unless the collector outlet temperature is at least 15°F higher than the inlet on the load side of the heat exchanger. This portion of the control system is not operating correctly, allowing the pumps to start up when the heat exchanger outlet on the load side is more than 50°F greater than the collector outlet temperature. Thermal energy is also allowed to flow from the load loop to the collector loop prior to the main pumps turning off. The cause of this incorrect operation is not known, but this problem, in combination with the erroneous operation of the auxiliary collector pumps, creates a situation that allows more energy to be radiated from the collectors at night than is collected during a sunny day. This problem is seriously affecting the efficiency of the installation.

Overheating of the collectors is a possibility in a system such as this with no thermal storage capability. To avoid this occurrence, a heat rejector was incorporated in the collector loop to transfer excess thermal energy to the atmosphere when the temperature of the heat exchanger outlet on the collection side exceeded 215°F. Occasional problems with control of the heat rejector have occurred during this six-month reporting period. The most serious problem has been failure of rejector operation to occur as collector fluid temperatures exceeded 250°F. Less serious, but wasteful problems have resulted in too frequent operation of the rejector. Occasionally, the rejector seems to operate in unison with the gas boiler.

The boiler in the space heating and cooling system is intended to be used as an auxiliary thermal energy source when the solar system is unable to support the demands. Apparent problems with the time clock on the boiler controls, and directions given to the on site personnel, have resulted in extremely large gas usage ($>10^9$ Btu/month). These are not actually problems with the solar equipment, but may result in apparent poor performance by the solar energy systems.

The causes of several of these problems have recently been identified [17] and corrective measures taken where possible. The freeze prevention thermostat controlling the auxiliary collector pumps was reset to a lower temperature to compensate for it apparently being out of calibration. The auxiliary pumps appear to be operating normally as a result of this. The unnecessary operation of the main collector pumps seems to be a result of logic in the control system allowing pump operation when the temperature of the load side of the heat exchanger is more than 60°F greater than the collector outlet. This problem requires investigation and correction at the site by the control system supplier.

Erratic operation of the heat rejector appears to have been corrected by a recalibration of the thermostat and relocation of the temperature sensor. Investigation into the extremely large usage of fossil fuel by the boiler revealed that the boiler was being fired 24 hours a day to extend its life by avoiding thermal stress due to cyclic operation. Analysis indicated that this was not a cost effective method of extending boiler life, and boiler operation is now enabled by a time clock.

These investigations and subsequent modifications were performed in late February and should show significant fuel savings in the future operation of the Irvine School. Mr. Jon Biemer of McCaughey & Smith Energy Associates is responsible for these investigations and modifications.

Collector performance during the six-month period covered by this report has been very consistent. The operational collector efficiency ranged from a monthly low in January of 37 percent to a high in November and March of 42 percent. The overall average for the period has been 40 percent. The Owens-Illinois collectors are very efficient at low incidence angles, and therefore readily collect energy early and late in the day. This characteristic results in the overall collector efficiency being only one percent lower than the operational collector efficiency for the six-month period.

The amount of solar energy collected reached a minimum in January of 57.25 million Btu and a maximum in March of 102.76 million Btu. The smallest system load also occurred in March as the result of a combination of moderate weather and the aforementioned system corrections. This resulted in the maximum solar fraction of 23 percent also occurring in March. The average solar fraction for the six-month period was 12 percent.

The space heating load was slightly larger than the space cooling load (670.87 versus 581.81 million Btu) during the reporting period, but the amount of solar energy consumed in attempt to meet this demand was much larger for the space cooling subsystem (394.33 versus 41.89 million Btu). An absorption

chiller always consumes a larger amount of energy than the cooling load it supports, and in this case, where the cooling load was relatively small for the large capacity chillers, the chillers could not operate at high efficiency. The result was that a large amount of thermal (solar and auxiliary) energy, 4,660.78 million Btu, was used for cooling during the six-month period.

Future months should show more efficient operation of the equipment at Irvine School as a result of the modifications which were made in February. Hopefully, the problems of auxiliary energy flowing to the collectors through the heat exchanger can be diagnosed and corrected in the future, further improving performance.

3. SYSTEM DESCRIPTION

The Irvine School is located in Central Orange County, California. The school is approximately 10 miles from the Pacific Ocean, and was built in 1971. The building contains 41,109 square feet of floor area, and is normally occupied five days a week by 850 children and 60 adults. Building occupancy is uniform throughout the year since the school operates on a trimester plan. The solar energy system was added to the existing building, and was designed to supply 50 percent of the annual building heating and cooling demand.

The solar energy installation includes 4,950 square feet of evacuated tubular glass collectors, a heat rejector, and a heat exchanger from the collector loop to the load loop. The collector array façes south at an angle of 25 degrees from the horizontal. Water is used as the medium for delivering solar energy from the collector array to the heat exchanger for transfer to the load subsystems. Existing load loop components were unaltered except for controls. These load loop components include a 4 million Btu per hour boiler, two 100-ton absorption chillers, 41 heating coils, and seven air handlers. Since heating demands are low due to the moderate climate and most of the load demand occurs during the day, no solar energy storage is provided. The collected solar energy is transferred directly from the collector loop to the load loop via the heat exchanger. If collected energy exceeds the load loop demand, excess energy is rejected via the heat rejector. The heat rejector is a water-to-air heat exchanger mounted on the roof and situated in the collector loop between the collector outlet and the load loop heat exchanger inlet. If the solar energy does not meet the full energy demand from the loads, the boiler is activated to make up the shortage before the hot water reaches the loads. The hot water is routed to the chillers or heating coils, or both, depending on the building demand. The hot water then returns to the heat exchanger to complete the cycle.

The system, shown schematically in Figure 3-1, has five modes of solar operation.

Mode 1 - Collector Protection: This mode occurs when the lower flow capacity (15 GPM) auxiliary collector pumps are turned on by a clock timer. This is normally before collection begins and is required to establish flow past the collector outlet sensor prior to initiation of solar energy collection (Mode 2). This mode is reentered daily at the completion of Mode 2 operation, and is subsequently terminated by the clock timer. Since no other freeze protection subsystem is provided, this mode is also entered when the outside ambient temperature is less than 38°F. The clock controller is overridden for freeze protection entry when this control temperature has been reached.

Mode 2 - Solar Energy Collection: This mode occurs when the main collector pump (125 GPM) is on. Mode entry requires a differential temperature of 15°F between the collector outlet and the load side inlet to the heat exchanger. When the differential temperature again drops below 15°F (adjustable), Mode 1 is reentered.

Mode 3 - Collector-to-Space Heating/Cooling: In this mode, heating and cooling loads may be active at the same time. This mode is enabled at all times, and receives energy from the solar energy system when available. If solar energy is not available, or is insufficient to satisfy the full demand, the auxiliary boiler is activated to supply the remaining demand. At night, this mode is normally disabled by the clock timer.

Mode 4 - Solar Heat Rejection: This mode occurs when excess solar energy is diverted from the collector loop and rejected to the environment through a liquid-to-air heat exchanger on the roof. This mode is entered if the temperature at the collector loop outlet from the heat exchanger exceeds a variable set point (approximately 215°F). Upon exceeding this set point temperature, a three-way valve is switched to initiate collector

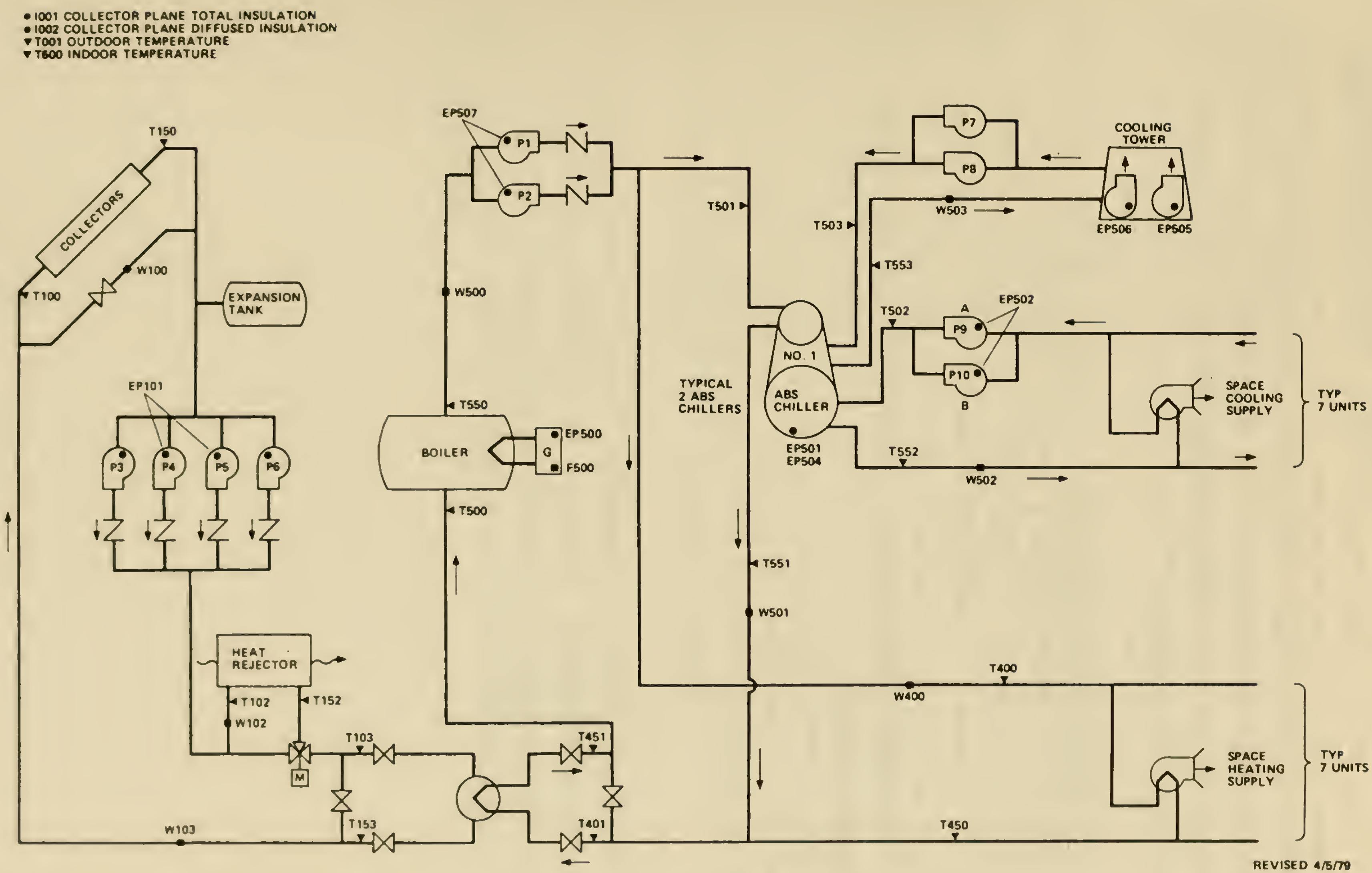

Figure 3-1. IRVINE SCHOOL SOLAR ENERGY SYSTEM SCHEMATIC

loop flow through the heat rejector, and the heat rejector fan is turned on to increase the air flow across its coils. When the heat exchanger outlet temperature drops below another variable set point (approximately 200°F), the three-way valve is reversed, the heat rejector fan is turned off, and this mode is terminated. This mode is employed when the collected solar energy exceeds the immediate demand from the load subsystems. This typically occurs on weekends.

<u>Mode 5 - Collector Backup Protection</u>: This mode is entered when the collector outlet temperature exceeds a set point (approximately 220°F). Control design assumes the collector pumps are not operating if this temperature is exceeded. In this mode, normally open solenoid valves allow city supply water to enter the collectors and drain out at the collector outlet. This mode protects against collector thermal shock damage if a power outage occurs.

4. PERFORMANCE EVALUATION TECHNIQUES

The performance of the Irvine School solar energy system is evaluated by calculating a set of primary performance factors which are based on those proposed in the intergovernmental agency report "Thermal Data Requirements and Performance Evaluation Procedures for the National Solar Heating and Cooling Demonstration Program" [3]. These performance factors quantify the thermal performance of the system by measuring the amount of energies that are being transferred between the components of the system. The performance of the system can then be evaluated based on the efficiency of the system in transferring these energies.

Data from monitoring instrumentation located at key points within the solar energy system are collected by the National Solar Data Network. This data is first formed into factors showing the hourly performance of each system component, either by summation or averaging techniques, as appropriate. The hourly factors then serve as a basis for the calculation of the daily and monthly performance of each component subsystem.

Each month a summary of overall performance of the Irvine School site and a detailed subsystem analysis are published. Monthly reports for the period covered by this System Performance Evaluation, September 1978 through March 1979, are available from the Technical Information Center, Oak Ridge, Tennessee 37830.

5. PERFORMANCE ASSESSMENT

The performance of the Irvine School solar energy system has been evaluated for the October 1978 through March 1979 time period. Two perspectives have been taken in this assessment. The first looks at the overall system view in which the total solar energy collected, the system load and the measured values for solar energy used and system solar fraction are presented. Also presented, where applicable, are the expected values for solar energy used and system solar fraction. The expected values have been derived from a modified f-chart* analysis which uses measured weather and subsystem loads as inputs. The model used in the analysis is based on manufacturers' data and other known system parameters. In addition, the solar energy system coefficient of performance (COP) at both the system and subsystem level has been presented. The second view presents a more in-depth look at the performance of individual components. Details relating to the performance of the collector array and storage subsystems are presented first, followed by details pertaining to the space heating subsystem. Included in this area are all parameters pertinent to the operation of each individual subsystem.

The performance assessment of any solar energy system is highly dependent on the prevailing weather conditions at the site during the period of performance. The original design of the system is generally based on the long-term averages for available insolation and temperature. Deviations from these long-term averages can significantly affect the performance of the system. Therefore, before beginning the discussion of actual system performance, a presentation of the measured and long-term averages for critical weather parameters has been provided.

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*f-chart is the designation of a procedure for designing solar heating systems. It was developed by the Solar Energy Laboratory, University of Wisconsin-Madison.

5.1 Weather Conditions

Average values of the daily incident solar energy in the plane of the collector array and the average outdoor temperature measured at the Irvine School site during the report period are presented in Table 5.1-1.

Also presented in Table 5.1-1 are the corresponding long-term average monthly values of the measured weather parameters. These data are taken from Reference Monthly Environmental Data for Systems in the National Solar Data Network [4]. A complete yearly listing of these values for the site is given in Appendix C.

Monthly values of heating and cooling degree-days are derived from daily values of ambient temperature. They are useful indications of the system heating and cooling loads. Heating degree-days and cooling degree-days are computed as the difference between daily average temperature and 65°F. For example, if a day's average temperature was 60°F, then five heating degree-days are accumulated. Likewise, if a day's average temperature was 80°F, then 15 cooling degree-days are accumulated. The total number of heating and cooling degree-days are summed monthly.

During the six-month period from October 1978 through March 1979, a daily average of 1,384 Btu/ft^2 of solar energy was incident on the collector array. This was eleven percent below the long-term daily average of 1,556 Btu/ft^2. The measured average ambient temperature for the period was 58°F, which was one degree below the long-term average of 59°F.

TABLE 5.1-1

WEATHER CONDITIONS

	Daily Incident Solar Energy Per Unit Area (25° Tilt)(Btu/Ft^2-Day)		Ambient Temperature (°F)		Heating Degree-Days		Cooling Degree-Days	
Month	Measured	Long-Term Average	Measured	Long-Term Average	Measured	Long-Term Average	Measured	Long-Term Average
Oct 78	1,546	1,707	70	67	6	48	144	107
Nov 78	1,344	1,453	58	61	200	155	0	23
Dec 78	1,231	1,309	52	56	381	295	0	0
Jan 79	1,042	1,379	54	54	355	339	0	0
Feb 79	1,487	1,615	55	56	288	273	0	7
Mar 79	1,651	1,870	59	57	205	247	14	0
Total	--	--	--	--	1,435	1,357	158	137
Average	1,384	1,556	58	59	239	226	26	23

5.2 System Thermal Performance

The thermal performance of a solar energy system is a function of the total solar energy collected and applied to the system load. The total system load is the sum of the energy requirements, both solar and auxiliary thermal, for each subsystem. The portion of the total load provided by solar energy is defined to be the solar fraction of the load. This solar fraction is the measure of performance for the solar energy system when compared to design or expected solar contribution.

The thermal performance of the Irvine School solar energy system is presented in Table 5.2-1 and Table 5.2-2. This performance assessment is based on the six-month period from October 1978 through March 1979.

During the six-month reporting period, a total of 489.47 million Btu of solar energy was collected and the total system load was 1,252.67 million Btu. The measured amount of solar energy delivered to the space heating and cooling load was 425.86 million Btu, which resulted in a measured system solar fraction of 12 percent.

The solar energy system COP (defined as the total solar energy delivered to the load divided by the total system operating energy) was 6.30 for the six-month period. When calculating separate COP values for each subsystem, the operating energy associated with that subsystem should be used as the denominator in the calculation. However, at a retrofit installation such as Irvine School, the only operating energy taxable to the solar subsystems is that operating energy associated with the collection loop. Therefore, the collection loop operating energy was equally divided and taxed to the three subsystems. This results in the space heating system having a lower COP value due to the relatively small space heating load. The collector array subsystem COP, the space heating subsystem solar COP, and the space cooling subsystem solar COP for the total period were 21.46, 1.84 and 17.29, respectively. These values again relate the amount of solar energy associated

TABLE 5.2-1

SYSTEM THERMAL PERFORMANCE

Month	Solar Energy Collected (Million Btu)	System Load (Million Btu)	Solar Energy Used (Million Btu)		Solar Fraction (Percent)	
			Expected	Measured	Expected	Measured
Oct 78	98.31	221.81	*	94.98	*	12
Nov 78	83.20	286.52		70.87		8
Dec 78	72.73	335.42		71.04		7
Jan 79	57.25	179.68		47.50		8
Feb 79	75.22	121.18		63.64		11
Mar 79	102.76	108.06		77.84		23
Total	489.47	1,252.67		425.86		--
Average	81.58	208.78		70.98		12

* The ECSS system at this site is of a type that cannot be analyzed by the f-chart procedure. Therefore, expected values of solar energy used and solar fraction are not available.

TABLE 5.2-2

SOLAR ENERGY SYSTEM COEFFICIENTS OF PERFORMANCE

Month	Solar Energy System COP	Collector Array Subsystem COP	Space Heating Subsystem Solar COP	Space Cooling Subsystem Solar COP
Oct 78	7.83	24.33	0.52	22.95
Nov 78	6.75	20.75	2.61	17.67
Dec 78	5.70	17.53	3.11	14.01
Jan 79	4.19	15.15	1.75	10.82
Feb 79	6.59	23.36	1.45	18.31
Mar 79	6.72	28.47	1.42	20.14
Total Period	6.30	21.46	1.84	17.29

with a particular subsystem to the amount of electrical energy required to operate that subsystem. As such, the COP serves as an indicator of both how well the system was designed and how well it operated. As mentioned above, at the Irvine School site the operating energy is divided equally between the three subsystems, and this is the reason that the space heating subsystem COP appears low with respect to the others.

There does not appear to be any strong relationship between system and subsystem COP values, and the system load or local weather conditions. This is somewhat unusual, but can be explained by the control system problems that were being experienced at the site during this period. These problems resulted in the solar energy portion of the system being operated in modes that at times were independent of heating and cooling demands or solar energy availability. This resulted in unusual values of subsystem operating energies and in nontypical amounts of solar energy being used to support the loads.

In light of the corrections that have recently been made to the control system, the values shown in Tables 5.2-1 and 5.2-2 should show more influence from local weather conditions in the future.

5.3 Subsystem Performance

The Irvine School solar energy installation may be divided into three subsystems:

1) Collector array
2) Space heating
3) Space cooling.

Each subsystem is evaluated by the techniques defined in Section 4 and is numerically analyzed each month for the monthly performance reports. This section presents the results of integrating the monthly data available on the three subsystems for the period October 1978 through March 1979.

5.3.1 Collector Array Subsystem

Collector array performance is described by comparison of the collected solar energy to the incident solar energy. The ratio of these two energies represents the collector array efficiency which may be expressed as

$$\eta_c = Q_s/Q_i \tag{1}$$

where: η_c = Collector Array Efficiency (CAREF)

Q_s = Collected Solar Energy (SECA)

Q_i = Incident Solar Energy (SEA).

The gross collector array area is 1,932 square feet. The measured monthly values of incident solar energy, collected solar energy, and collector array efficiency are presented in Table 5.3.1-1.

Evaluation of collector efficiency using operational incident energy and compensating for the difference between gross collector array area and the gross collector area yields operational collector efficiency. Operational collector efficiency, η_{co}, is computed as follows:

$$\eta_{co} = Q_s/\left(Q_{oi} \times \frac{A_p}{A_a}\right) \tag{2}$$

where: Q_s = Collected Solar Energy (SECA)

Q_{oi} = Operational Incident Energy (SEOP)

A_p = Gross Collector Area (product of the number of collectors and the total envelope area of one unit) (GCA)

A_a = Gross Collector Array Area (total area perpendicular to the solar flux vector including all mounting, connecting and transport hardware (GCAA).

Note: The ratio $\frac{A_p}{A_a}$ is typically 1.0 for most collector array configurations.

TABLE 5.3.1-1

COLLECTOR ARRAY PERFORMANCE

Month	Incident Solar Energy (Million Btu)	Collected Solar Energy (Million Btu)	Collector Array Efficiency	Operational Incident Energy (Million Btu)	Operational Collector Efficiency
Oct 78	237.27	98.31	0.41	236.90	0.41
Nov 78	199.66	83.20	0.42	199.50	0.42
Dec 78	188.88	72.73	0.39	188.66	0.39
Jan 79	159.88	57.25	0.36	155.27	0.37
Feb 79	206.04	75.22	0.37	199.24	0.38
Mar 79	253.29	102.76	0.41	245.15	0.42
Total	1,245.02	489.47	--	1,224.72	--
Average	207.50	81.58	0.39	204.12	0.40

This latter efficiency term is not the same as collector efficiency as represented by the ASHRAE Standard 93-77 [5]. Both operational collector efficiency and the ASHRAE collector efficiency are defined as the ratio of actual useful energy collected to solar energy incident upon the collector and both use the same definition of collector area. However, the ASHRAE efficiency is determined from instantaneous evaluation under tightly controlled, steady state test conditions, while the operational collector efficiency is determined from the actual conditions of daily solar energy system operation. Measured monthly values of operational incident energy and computed values of operational collector efficiency are also presented in Table 5.3.1-1.

Collector array efficiency may be viewed from two perspectives. The first assumes that the efficiency be based upon all available solar energy; however, that point of view makes the operation of the control system a part of array efficiency. For example, energy may be available at the collector, but the collector fluid temperature is below the control minimum, thus the energy is not collected. The monthly efficiency computed by this method is listed in the column entitled "Collector Array Efficiency" in Table 5.3.1-1.

The second viewpoint assumes the efficiency be based upon only the incident energy during periods of collection. The monthly efficiency computed by this method is listed in the column entitled "Operational Collector Array Efficiency." Efficiency computed by this method is used in the following discussion.

The Irvine School collector system consists of Owens-Illinois evacuated tube collectors. The tubes are arranged in modules, with each module consisting of 24 tubes, 12 up and 12 down, in a series flow arrangement. There are 10 of these modules per bank, and 18 banks arranged on the roof. This amounts to a total of 180 modules composed of 4,320 tubes. Table 5.3.1-2 presents a comparison of the actual performance of the collector array for the month of December against four predictions of performance which are based on instantaneous efficiency curves. December was chosen as the example month since the collector was operational on 30 of 31 days during the month, and the monthly collector array efficiency was near the average value for the six-month period.

TABLE 5.3.1-2

ENERGY GAIN COMPARISON
DECEMBER

SITE: IRVINE SCHOOL IRVINE, CA

DAY	ACTUAL	ERROR: FIELD DERIVED: MONTH	ERROR: FIELD DERIVED: LONG TERM	ERROR: FIELD DERIVED: 2ND ORDER	ERROR: LAB: PANEL
1	2.742E+05	-0.164	-0.173	-0.581	0.121
2	3.305E+06	0.083	0.064	-0.191	0.006
3	3.382E+06	0.045	0.026	-0.198	-0.046
4	3.123E+06	0.025	0.007	-0.229	-0.052
5	9.379E+05	-0.016	-0.028	-0.484	0.243
6	2.991E+06	-0.031	-0.048	-0.296	-0.084
7	3.150E+06	-0.029	-0.046	-0.277	-0.097
8	2.897E+06	-0.070	-0.086	-0.316	-0.128
9	3.368E+06	0.150	0.130	-0.167	0.089
10	2.971E+06	-0.008	-0.025	-0.249	-0.086
11	3.290E+06	0.057	0.038	-0.179	-0.042
12	0.000E+00	0.000	0.000	0.000	0.000
13	3.064E+06	0.014	-0.004	-0.223	-0.073
14	2.826E+06	0.038	0.020	-0.248	-0.017
15	1.071E+06	-0.167	-0.178	-0.532	-0.025
16	1.637E+06	-0.122	-0.136	-0.437	-0.091
17	4.911E+04	10.375	25.686	-0.804	-1.413
18	3.217E+05	0.202	0.212	-0.688	-7.441
19	1.866E+06	0.098	0.081	-0.270	0.105
20	3.460E+06	0.083	0.064	-0.177	-0.005
21	2.470E+06	0.043	0.025	-0.237	-0.019
22	2.981E+06	0.093	0.074	-0.190	0.021
23	2.602E+06	0.023	0.005	-0.260	-0.031
24	2.623E+06	0.055	0.038	-0.248	0.011
25	1.065E+06	0.062	0.051	-0.462	0.404
26	1.169E+06	0.024	0.011	-0.444	0.244
27	1.838E+06	-0.004	-0.020	-0.359	0.027
28	1.416E+06	-0.027	-0.042	-0.390	0.026
29	1.702E+06	-0.028	-0.042	-0.388	0.022
30	2.369E+06	0.020	0.003	-0.292	-0.006
31	3.126E+06	0.079	0.060	-0.207	0.013
	6.735E+07	0.025	0.008	-0.282	-0.007

CURVE	COEFFICIENTS: A0 (BETA)	COEFFICIENTS: A1 (FULL)	COEFFICIENTS: A2 (*)	COEFFICIENTS: R**2
PANEL	0.570	-0.240	N.A.	N.A.
MONTH	0.416	-0.046	N.A.	0.001
LT1ST	0.426	-0.051	N.A.	0.001
LT2ND	0.316	0.316	0.000	N.A.

Instantaneous efficiency curves are derived from laboratory test data supplied by the collector manufacturer and from three empirical sources: a linear regression line fit through field data obtained in December; a linear regression line fit through all field data in the base; and a curvilinear (second order) regression line fit through all field data in the base (the base data consists of all measurements relating to collector array performance made from October through December 1978).

Each error value presented in the error field of Table 5.3.1-2 is computed by the equation

$$\text{error} = (A - P)/P \tag{3}$$

where:

A is the actual energy gain of the collector array shown in column one (million Btu/day)

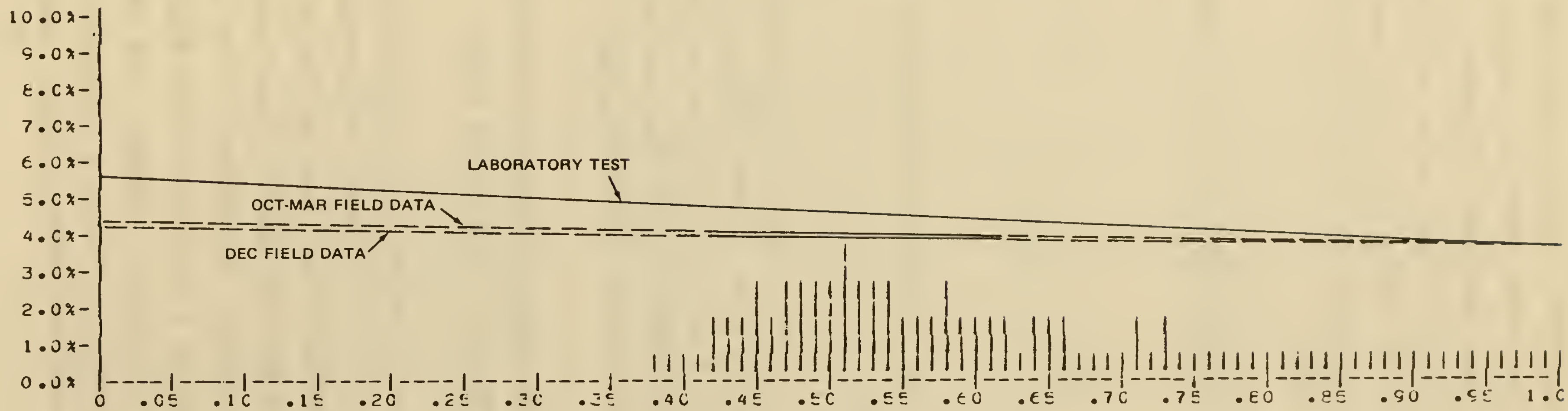
P is the predicted energy gain of the collector array based on projecting the measured operating point to the applicable instantaneous efficiency curve and multiplying by the measured insolation level and collector array area and then summing over all the measured operating points (million Btu/day).

The computed error is then a measure of how well the particular prediction curve fits the reality of dynamic operating conditions in the field.

Figure 5.3.1-1 presents a histogram of the collector array operating points for December. Also presented in Figure 5.3.1-1 are linear instantaneous efficiency curves based on controlled laboratory test data supplied by the collector manufacturer, field data for the month of December and long-term field data for the October through March period. The ordinate of the graph shown in Figure 5.3.1-1 has a printed range of 0 to 10 percent to display the distribution of collector array operating points. However, the value printed on the ordinate should be multiplied by 10 when the intercepts of the linear instantaneous efficiency curves are being evaluated (these values range from 0 to 100 percent).

IRVINE SCHOOL IRVINE, CA

COLLECTOR TYPE: OWENS-ILLINOIS COLLECTOR MODEL: SUNPAK



FLUID PROPERTIES - DECEMBER

WATER				
	COEFFICIENTS			
PROPERTY	A0	A1	A2	A3
SPECIFIC HEAT	1.011E+00	-2.348E-04	1.037E-06	
DENSITY	8.346E+00	4.129E-04	-9.961E-06	

ARRAY FLOW RATE 125.87 GPM

PANEL FLOW RATE 0.03 GPM

AVERAGE TEMPERATURE GAIN 5.10 DEGR FAHRENHEIT

LONG TERM CURVE FIT VALID FROM 0.381 TO 0.614 .

Figure 5.3.1-1. COLLECTOR ARRAY OPERATING POINT HISTOGRAM AND INSTANTANEOUS EFFICIENCY CURVES

The collector array operating points, X, are calculated each scan by the equation

$$X = (T_{f,i} - T_a)/I \qquad (4)$$

where:

$T_{f,i}$ is the inlet temperature of the collector array transport fluid (°F)

T_a is the temperature of the ambient air (°F)

I is the insolation rate (Btu/Ft^2-Hr).

Examination of the operating point histogram indicates that the predominant region of collector array operation occurred for operating points between 0.42 to 0.62. This leads to the expectation that the operational collector array efficiency would typically be on the order of 0.40, which is in agreement with the data presented in Table 5.3.1-1.

These three curves are in relatively close agreement. The discrepancy that exists between the controlled laboratory test and the others is most likely due to two causes. First, different reflective surfaces were used behind the Irvine School collectors than were used behind the laboratory test collector. This type of collector receives a significant portion of its energy from reflected radiation, and therefore is sensistive to the reflective surface used. Second, the laboratory test collector represents radiation being received from a fixed angle of the sun's elevation above the horizon, in this case 40 degrees from prerpendicular; results shown from Irvine School are for the actual position of the sun in the sky during the course of a day. Knowing this, the curves appear to be in very good agreement. Near the right side of the figure, the field data is from low gain situations, such as when the sun is just above the horizon at a large angle of incidence. This is not

unlike the laboratory data taken at a 40 degree angle of incidence. As the sun rises in the sky the operating point moves to the left across the chart. More direct, but less reflected, energy is received as the angle of incidence becomes smaller, and the efficiency falls below that seen at the 40 degree angle of incidence.

In summary, the data collected from Irvine School is in very close agreement with the manufacturers supplied test data, indicating excellent installation of the collectors at the site. Additional information concerning collector array analysis in general may be found in a forthcoming paper [15] that describes collector array analysis procedures in detail and presents the results of analysis performed on numerous collector array installations across the United States.

5.3.2 Space Heating Subsystem

The performance of the space heating subsystem is described by comparing the amount of solar energy supplied to the subsystem with the energy required to satisfy the total space heating load. The energy required to satisfy the total load consists of both solar energy and auxiliary thermal energy. The ratio of solar energy supplied to the load to the total load is defined as the heating solar fraction. The calculated heating solar fraction is the indicator of performance for the subsystem because it defines the percentage of the total space heating load supported by solar energy.

The performance of the Irvine School space heating subsystem is presented in Table 5.3.2-1. For the six-month period from October 1978 through March 1979, the solar energy system supplied a total of 41.89 million Btu to the space heating load. The total heating load for this period was 670.87 million Btu, and the average monthly solar fraction was six percent. Heating system performance is somewhat low during this period due to low insolation resulting from the shorter days, the control problems mentioned earlier and the time at which the heating demand occurs. Nothing can be done to lengthen the days, but improvement should be evident in the next Performance Evaluation Report covering the period with more daylight hours. Corrections to the control system were made in February, and possibly this contributed to the doubling of the solar fraction in March. The significant control problem that allows thermal energy to flow in both directions across the heat exchanger still exists.

The third problem, concerning the time at which the heating demand occurs, applies to the space cooling subsystem also. At Irvine School, with no storage system, the solar energy system cannot support loads which occur when the sun is not available. This caused significant reduction in solar fractions prior to March when the boiler was available and in use 24 hours a day. During this time the demand was almost fully satisfied by the boiler before the solar energy system had a chance to operate.

TABLE 5.3.2-1

HEATING SUBSYSTEM PERFORMANCE

Month	Space Heating Load (Million Btu)	Energy Consumed (Million Btu)			Measured Solar Fraction (Percent)
		Solar	Auxiliary Thermal	Auxiliary	
Oct 78	28.02	2.12	26.03	34.96	8
Nov 78	178.53	10.46	168.94	215.86	6
Dec 78	233.84	12.90	215.13	283.24	6
Jan 79	120.08	6.60	118.71	164.71	5
Feb 79	70.74	4.68	70.29	138.65	6
Mar 79	39.66	5.13	42.40	61.28	13
Total	670.87	41.89	641.50	898.70	--
Average	111.81	6.98	106.92	149.78	6

An improvement in solar fraction, and a corresponding reduction in auxiliary fuel usage, might be realized by delaying the availability of the gas boiler. This would give the solar system a chance to support the load. If the solar system was not capable, the auxiliary system could then be allowed to supply the necessary thermal energy. This might be achieved by simply changing the setting of the time clock that determines boiler availability to a time after sunrise. Adjustment would be required periodically throughout the year as the time of solar energy availability changed. Some experimentation may be necessary until an optimum delay time is found.

5.3.3 Space Cooling Subsystem

The performance of the space cooling subsystem is described by comparing the amount of solar energy supplied to the subsystem with the energy required to satisfy the total space cooling load. The energy required to satisfy the total load consists of both solar energy and auxiliary thermal energy. The ratio of solar energy supplied to the load to the total load is defined as the cooling solar fraction. The calculated cooling solar fraction is the indicator of performance for the subsystem because it defines the percentage of the total space cooling load supported by solar energy.

The performance of the Irvine School space cooling subsystem is presented in Table 5.3.3-1. For the six-month period from October 1978 through March 1979, the solar energy system supplied a total of 394.33 million Btu to the space cooling load. The total cooling load for the six-month period was 581.81 million Btu and the solar fraction during the period was 14 percent. As in all absorption chillers, the amount of thermal energy consumed is larger than the cooling load.

The same comments that were made for the poor solar fraction of the space heating subsystem apply to the space cooling subsystem. Changes made to the control system in February also increased the solar fraction of the cooling subsystem in March.

Absorption chillers are used to perform the space cooling at Irvine School, independent of the source of thermal energy (either solar energy or fossil fuel). Calculations of the coefficient of performance (COP) of the chillers in the monthly reports have indicated values ranging from 0.10 to 0.24, with an average of 0.14 for the six-month period. These values seem exceptionally low, indicating inefficient operation of the chillers.

An investigation of the two 100-ton ARKLA absorption chillers was performed as part of a study to be published shortly [16]. The results indicate that the chillers are performing near design specification, but possibly they are not of the optimum design for the space cooling loads experienced at

TABLE 5.3.3-1

COOLING SUBSYSTEM PERFORMANCE

Month	Space Cooling Load (Million Btu)	Energy Consumed (Million Btu)			Measured Solar Fraction (Percent)
		Solar	Auxiliary Thermal	Auxiliary	
Oct 78	193.79	92.73	1,003.94	1,388.29	13
Nov 78	107.99	70.87	1,066.75	1,385.79	11
Dec 78	101.58	58.15	968.16	1,276.97	10
Jan 79	59.61	40.91	556.03	742.56	12
Feb 79	50.44	58.96	452.17	854.99	18
Mar 79	68.40	72.71	219.40	279.44	29
Total	581.81	394.33	4,266.45	5,928.04	--
Average	96.97	65.72	711.08	988.01	14

Irvine School. In actuality, when the load is small, such as in the morning when space cooling is first needed, internal by-passes in the chiller prevent absorption cooling from taking place until the water returning from the cooling tower exceeds approximately 85°F. Meanwhile thermal energy is continuously being sent to the generator portion of the chiller; part of it is used to heat up the relatively large generator and associated hardware, and the remainder is lost to the atmosphere or sent to the cooling tower. The result is that the small cooling load is met at the expense of a relatively large amount of thermal energy, therefore a small COP is measured.

When the cooling load increases, the by-pass flow no longer occurs and absorption chilling occurs as it should with a more normal value for the COP. Apparently there are no modifications that can be made economically to the existing chillers to allow them to efficiently support a small load. An improved performance would probably result from the use of several smaller capacity chillers.

Figure 5.3.3-1 shows the variation of the COP of the 100-ton chiller as it operates during the course of a day at Irvine School. On this particular day, the cooling load was large enough to allow a nominal COP to be achieved. During the six months of this report however, the cooling loads experienced on the average were similar to those experienced during the 8, 9, and 10 o'clock hours shown in the data for March 5, and therefore averaged 0.14 for the period.

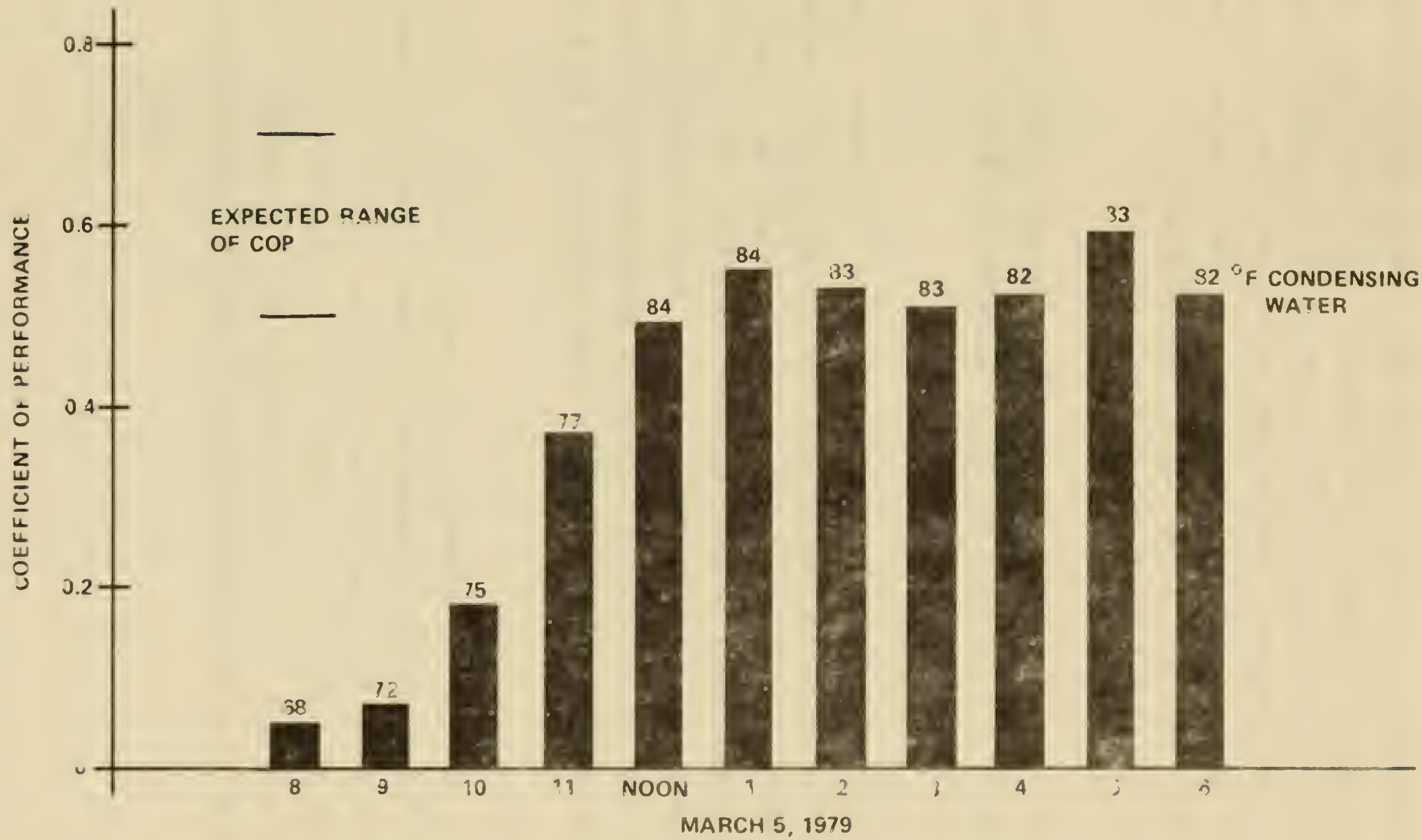


Figure 5.3.3-1. IRVINE SCHOOL CHILLER PERFORMANCE

5.4 Operating Energy

Operating energy for the Irvine School solar energy system is defined as the energy required to transport solar energy to the point of use. Total operating energy for this system consists of energy collection and storage subsystem operating energy and space heating and cooling subsystem operating energies. Operating energy is electrical energy that is used to support the subsystems without affecting their thermal state. Measured monthly values for subsystem operating energy are presented in Table 5.4-1.

Total system operating energy for the Irvine School is that electrical energy required to operate the main and auxiliary pumps in the collector loop. These are shown as pumps P3 through P6 in Figure 3-1.

Although electrical energy is required to operate the pumps, blowers and the absorption chiller in the loop on the load side of the heat exchanger, all of this equipment would be used if the solar system were not present. Therefore the solar system cannot be taxed by their operation. Since the operating energy required for the collection system is small and quite constant and, since both heating and cooling is required during most months, the operating energy is equally charged to the ECSS, space heating, and space cooling subsystems.

For the six-month period covered by this report, a total of 68.46 million Btu of electrical operating energy was consumed. During the same time, a total of 425.86 million Btu of solar energy was supplied to the space heating load and 394.33 million Btu of solar energy was applied to the space cooling load. Therefore, for every one million Btu of solar energy delivered to the load, 0.08 million Btu (or 24.46 kwh) of electrical operating energy was expended.

TABLE 5.4.1

OPERATING ENERGY

Month	ECSS Operating Energy (Million Btu)	Space Heating Operating Energy (Million Btu)	Space Cooling Operating Energy (Million Btu)	Total System Operating Energy (Million Btu)
Oct 78	4.04	4.04	4.04	12.13
Nov 78	4.01	4.01	4.01	12.04
Dec 78	4.15	4.15	4.15	12.46
Jan 79	3.78	3.78	3.78	11.35
Feb 79	3.22	3.22	3.22	9.66
Mar 79	3.61	3.61	3.61	10.82
Total	22.82	22.82	22.82	68.46
Average	3.80	3.80	3.80	11.41

5.5 Energy Savings

Solar energy system savings are realized whenever energy provided by the solar energy system is used to meet system demands which would otherwise be met by auxiliary energy sources. The operating energy required to provide solar energy to the load subsystems is subtracted from the solar energy contribution, and the resulting energy savings are adjusted to reflect the coefficient of performance (COP) of the auxiliary source being supplanted by solar energy.

The auxiliary source at the Irvine School consists of the gas fired boiler that was at the school prior to the installation of the solar energy system. This unit is considered to be 60 percent efficient for computational purposes, to that 60 percent of the fossil fuel energy supplied to it is delivered to the space heating load.

Energy savings for October 1978 through March 1979 are presented in Table 5.5-1. For this period, the average net fossil savings were 121.17 million Btu per month. This was achieved with an average net electrical expense of 11.41 million Btu, or 3343.13 kwh, per month.

TABLE 5.5-1

ENERGY SAVINGS

Month	Fossil Energy Savings (Million Btu)		Solar Operating Energy (Million Btu)	Net Savings			Fossil Equivalent At Source (Million Btu)
				Electrical		Fossil	
	Space Heating	Space Cooling		Million Btu	kwh	Million Btu	
Oct 78	3.53	154.54	12.13	-12.13	-3,554.09	158.07	-40.39
Nov 78	17.44	118.11	12.04	-12.04	-3,527.72	135.55	-40.09
Dec 78	21.49	96.91	12.46	-12.46	-3,650.78	118.41	-41.49
Jan 79	11.00	68.18	11.35	-11.35	-3,325.55	79.17	-37.80
Feb 79	7.80	98.26	9.66	-9.66	-2,830.38	106.07	-32.17
Mar 79	8.55	121.18	10.82	-10.82	-3,170.26	129.73	-36.03
Total	69.81	657.18	68.46	-68.46	-20,058.78	727.00	-227.97
Average	11.64	109.53	11.41	-11.41	-3,343.13	121.17	-38.00

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APPENDIX A

DEFINITION OF PERFORMANCE FACTORS AND SOLAR TERMS

COLLECTOR ARRAY PERFORMANCE

The collector array performance is characterized by the amount of solar energy collected with respect to the energy available to be collected.

- INCIDENT SOLAR ENERGY (SEA) is the total insolation available on the gross collector array area. This is the area of the collector array energy-receiving aperture, including the framework which is an integral part of the collector structure.

- OPERATIONAL INCIDENT ENERGY (SEOP) is the amount of solar energy incident on the collector array during the time that the collector loop is active (attempting to collect energy).

- COLLECTED SOLAR ENERGY (SECA) is the thermal energy removed from the collector array by the energy transport medium.

- COLLECTOR ARRAY EFFICIENCY (CAREF) is the ratio of the energy collected to the total solar energy incident on the collector array. It should be emphasized that this efficiency factor is for the collector array, and available energy includes the energy incident on the array when the collector loop is inactive. This efficiency must not be confused with the more common collector efficiency figures which are determined from instantaneous test data obtained during steady state operation of a single collector unit. These efficiency figures are often provided by collector manufacturers or presented in technical journals to characterize the functional capability of a particular collector design. In general, the collector panel maximum efficiency factor will be significantly higher than the collector array efficiency reported here.

ENERGY COLLECTION AND STORAGE SUBSYSTEM

The Energy Collection and Storage Subsystem (ECSS) is composed of the collector array, the distribution loop and other components in the system design which are necessary to mechanize the collector and energy distribution and conversion equipment.

- INCIDENT SOLAR ENERGY (SEA) is the total insolation available on the gross collector array area. This is the area of the collector array energy-receiving aperture, including the framework which is an integral part of the collector structure.

- AMBIENT TEMPERATURE (TA) is the average temperature of the outdoor environment at the site.

- ENERGY TO LOADS (SEL) is the total thermal energy transported from the ECSS to all load subsystems.

- AUXILIARY THERMAL ENERGY TO ECSS (CSAUX) is the total auxiliary supplied to the ECSS, including auxiliary energy added to the storage tank, heating devices on the collectors for freeze-protection, etc.

- ECSS OPERATING ENERGY (CSOPE) is the critical operating energy required to support the ECSS heat transfer loops.

SPACE HEATING SUBSYSTEM

The space heating subsystem is characterized by performance factors accounting for the complete energy flow to and from the subsystem. The average building temperature and the average ambient temperature are tabulated to indicate the relative performance of the subsystem in satisfying the space heating load and in controlling the temperature of the conditioned space.

- SPACE HEATING LOAD (HL) is the sensible energy added to the air in the building.

- SOLAR FRACTION OF LOAD (HSFR) is the fraction of the sensible energy added to the air in the building derived from the solar energy system.

- SOLAR ENERGY USED (HSE) is the amount of solar energy supplied to the space heating subsystem.

- OPERATING ENERGY (HOPE) is the amount of electrical energy required to support the subsystem, (e.g., fans, pumps, etc.) and which is not intended to affect directly the thermal state of the subsystem.

- AUXILIARY THERMAL USED (HAT) is the amount of energy supplied to the major components of the subsystem in the form of thermal energy in a heat transfer fluid or its equivalent. This term also includes the converted electrical and fossil fuel energy supplied to the subsystem.

- AUXILIARY ELECTRICAL FUEL (HAE) is the amount of electrical energy supplied directly to the subsystem.

- ELECTRICAL ENERGY SAVINGS (HSVE) is the estimated difference between the electrical energy requirements of an alternative conventional system (carrying the full load) and the actual electrical energy required by the subsystem.

- BUILDING TEMPERATURE (TB) is the average heated space dry bulb temperature.

- AMBIENT TEMPERATURE (TA) is the average ambient dry bulb temperature at the site.

SPACE COOLING SUBSYSTEM

The space cooling subsystem is characterized by performance factors accounting for the complete energy flow to and from the subsystem. The average building temperature and the average ambient temperature are tabulated to indicate the relative performance of the subsystem in satisfying the space cooling load and in controlling the temperature of the conditioned space.

- SPACE COOLING LOAD (CL) is the total energy, including sensible and latent, removed from the air in the space-cooling area of the building.

- SOLAR FRACTION OF LOAD (CSFR) is the percentage of the demand which is supported by solar energy.

- SOLAR ENERGY USED (CSE) is the amount of solar energy supplied to the space-cooling subsystem.

- OPERATING ENERGY (COPE) is the amount of electrical energy required to support the subsystem, (e.g., fans, pumps, etc.) and which is not intended to affect directly the thermal state of the subsystem.

- AUXILIARY THERMAL USED (CAT) is the amount of energy supplied to the major components of the subsystem in the form of thermal energy in a heat transfer fluid, or its equivalent. This term also includes the converted electrical and fossil fuel supplied to the subsystem.

- AUXILIARY ELECTRICAL FUEL (CAE) is the amount of electrical energy supplied directly to the subsystem.

- ELECTRICAL ENERGY SAVINGS (CSVE) is the estimated difference between the electrical energy requirements of an alternative conventional system (carrying the full load) and the actual electrical energy required by the subsystem.

ENVIRONMENTAL SUMMARY

The environmental summary is a collection of the weather data which is generally instrumented at each site in the program. It is tabulated in this data report for two purposes--as a measure of the conditions prevalent during the operation of the system at the site, and as an historical record of weather data for the vicinity of the site.

- TOTAL INSOLATION (SE) is accumulated total solar energy incident upon the gross collector array measured at the site.

- AMBIENT TEMPERATURE (TA) is the average temperature of the environment at the site.

- WIND DIRECTION (WDIR) is the average direction of the prevailing wind.

- WIND SPEED (WIND) is the average wind speed measured at the site.

- DAYTIME AMBIENT TEMPERATURE (TDA) is the temperature during the period from three hours before solar noon to three hours after solar noon.

APPENDIX B

SOLAR ENERGY SYSTEM PERFORMANCE EQUATIONS FOR THE IRVINE SCHOOL

I. INTRODUCTION

Solar energy system performance is evaluated by performing energy balance calculations on the system and its major subsystems. These calculations are based on physical measurement data taken from each subsystem every 320 seconds. This data is then numerically combined to determine the hourly, daily, and monthly performance of the system. This appendix describes the general computational methods and the specific energy balance equations used for this evaluation.

Data samples from the system measurements are numerically integrated to provide discrete approximations of the continuous functions which characterize the system's dynamic behavior. This numerical integration is performed by summation of the product of the measured rate of the appropriate performance parameters and the sampling interval over the total time period of interest.

There are several general forms of numerical integration equations which are applied to each site. These general forms are exemplified as follows: The total solar energy available to the collector array is given by

$$\text{SOLAR ENERGY AVAILABLE} = (1/60)\ \Sigma\ [\text{I001} \times \text{AREA}] \times \Delta\tau$$

where I001 is the solar radiation measurement provided by the pyranometer in Btu/ft^2-hr, AREA is the area of the collector array in square feet, $\Delta\tau$ is the sampling interval in minutes, and the factor (1/60) is included to correct the solar radiation "rate" to the proper units of time.

Similarly, the energy flow within a system is given typically by

$$\text{COLLECTED SOLAR ENERGY} = \Sigma\ [\text{M100} \times \Delta H] \times \Delta\tau$$

where M100 is the mass flow rate of the heat transfer fluid in lb_m/min and ΔH is the enthalpy change, in Btu/lb_m, of the fluid as it passes through the heat exchanging component.

For a liquid system ΔH is generally given by

$$\Delta H = \overline{C}_p\ \Delta T$$

where $\overline{C}_p$ is the average specific heat, in Btu/(lb_m-°F), of the heat transfer fluid and ΔT, in °F, is the temperature differential across the heat exchanging component.

For an air system ΔH is generally given by

$$\Delta H = H_a(T_{out}) - H_a(T_{in})$$

where $H_a(T)$ is the enthalpy, in Btu/lb_m, of the transport air evaluated at the inlet and outlet temperatures of the heat exchanging component.

$H_a(T)$ can have various forms, depending on whether or not the humidity ratio of the transport air remains constant as it passes through the heat exchanging component.

For electrical power, a general example is

$$\text{ECSS OPERATING ENERGY} = (3413/60)\ \Sigma\ [\text{EP100}] \times \Delta\tau$$

where EP100 is the power required by electrical equipment in kilowatts and the two factors (1/60) and 3413 correct the data to Btu/min.

These equations are comparable to those specified in "Thermal Data Requirements and Performance Evaluation Procedures for the National Solar Heating and Cooling Demonstration Program." This document, given in the list of references, was prepared by an inter-agency committee of the government, and presents guidelines for thermal performance evaluation.

Performance factors are computed for each hour of the day. Each numerical integration process, therefore, is performed over a period of one hour. Since long-term performance data is desired, it is necessary to build these hourly performance factors to daily values. This is accomplished, for energy parameters, by summing the 24 hourly values. For temperatures, the hourly values are averaged. Certain special factors, such as efficiencies, require appropriate handling to properly weight each hourly sample for the daily value computation. Similar procedures are required to convert daily values to monthly values.

EQUATIONS USED IN MONTHLY PERFORMANCE REPORT

NOTE: - MEASUREMENT NUMBERS REFERENCE SYSTEM SCHEMATIC FIGURE 3-1

SITE SUMMARY REPORT

INCIDENT SOLAR ENERGY (BTU)

$$SEA = (1/60) \times \Sigma [I001 \times AREA] \times \Delta\tau$$

INCIDENT SOLAR ENERGY PER UNIT AREA (BTU/FT^2)

$$SE = (1/60) \times \Sigma\ I001 \times \Delta\tau$$

ENTHALPY FUNCTION FOR WATER (BTU/LBM)

$$HWD\ (T_2, T_1) = \int_{T_1}^{T_2} C_p(T)dT$$

THIS FUNCTION COMPUTES THE ENTHALPY CHANGE OF WATER AS IT PASSES THROUGH A HEAT EXCHANGING DEVICE.

COLLECTED SOLAR ENERGY (BTU)

$$SECA = \Sigma [M100 \times HWD(T150, T100)] \times \Delta\tau$$

COLLECTED SOLAR ENERGY PER UNIT AREA (BTU/SQ. FT.)

$$SEC = \Sigma [M100 \times HWD(T150, T100)/AREA] \times \Delta\tau$$

AVERAGE AMBIENT TEMPERATURE (DEGREES F)

$$TA = (1/60) \times \Sigma\ T001 \times \Delta\tau$$

TOTAL SYSTEM OPERATING ENERGY (BTU)

SYSOPE = ECSS OPERATING ENERGY + HEATING OPERATING ENERGY + COOLING OPERATING ENERGY

AVERAGE BUILDING TEMPERATURE (DEGREES F)

$$TB = (1/60) \times \Sigma\ T600 \times \Delta\tau$$

ECSS SOLAR CONVERSION EFFICIENCY

CSCEF = SOLAR ENERGY TO LOAD/INCIDENT SOLAR ENERGY

ECSS OPERATING ENERGY (BTU)

CSOPE = $56.8833 \times \Sigma\ EP101 \times \Delta\tau$

LOAD SUBSYSTEM SUMMARY:

HEATING FOSSIL SAVINGS (BTU)

HSVF = SOLAR ENERGY TO HEATING/0.6.

COOLING FOSSIL SAVINGS (BTU)

CSVF = SOLAR ENERGY TO COOLING/0.6.

TOTAL FOSSIL SAVINGS = HSVF + CSVF

TOTAL ELECTRICAL SAVINGS (BTU)

TSVE = -CSOPE

TOTAL ENERGY CONSUMED (BTU)

TECSM = AUXILIARY THERMAL ENERGY + OPERATING ENERGY + SOLAR ENERGY COLLECTED

LOAD SUBSYSTEM SUMMARY (BTU):

HEATING LOAD

HL = $\Sigma\ [M400 \times HWD\ (T400, T450)] \times \Delta\tau$

COOLING LOAD

CL = $\Sigma\ [M502 \times HWD\ (T502, T552)] \times \Delta\tau$

THERMAL LOAD FOR COOLING

HLC = $\Sigma\ [M501 \times HWD\ (T501, T551)] \times \Delta\tau$

SYSTEM LOAD (BTU)

SYSL = HL + CL

HEATING SOLAR FRACTION (PERCENT)

HSFR = 100 x (HEATING SOLAR ENERGY/HEATING LOAD)

COOLING SOLAR FRACTION (PERCENT)

CSFR = 100 x (COOLING DONE WITH SOLAR ENERGY/COOLING LOAD)

SOLAR ENERGY USED:

HEATING SOLAR ENERGY (BTU)

HSE = [HL/(HL + HLC)] x TOTAL SOLAR ENERGY TO LOADS

COOLING SOLAR ENERGY (BTU)

CSE = [HLC/(HL + HLC)] x TOTAL SOLAR ENERGY TO LOADS

TOTAL SOLAR ENERGY TO LOADS (BTU)

SEL = HSE + CSE

OPERATIONAL INCIDENT ENERGY (BTU)

SEOP = $(1/60)\ \Sigma\ [I001 \times AREA] \times \Delta\tau$

WHENEVER COLLECTOR PUMP IS RUNNING

COLLECTOR ARRAY EFFICIENCY

CAREF = SECA/SEA

ECSS SOLAR CONVERSION EFFICIENCY

CSCEF = SOLAR ENERGY TO LOAD / INCIDENT SOLAR ENERGY

DIFFUSE INSOLATION (BTU/FT^2)

$= (1/60)\ \Sigma\ I002 \times \Delta\tau$

DAYTIME AMBIENT TEMP (DEGREES F)

TDA = $(1/360)\ \Sigma\ T001 \times \Delta\tau$

$\pm$ 3 HOURS FROM SOLAR NOON

OPERATING ENERGY (BTU):

HEATING OPERATING ENERGY

HOPE = $[HL/(HL + HLC)] \times 56.8833 \times \Sigma\ (EP500 + EP507) \times \Delta\tau$

COOLING OPERATING ENERGY

COPE = $[HLC/(HL + HLC)] \times 56.8833 \times \Sigma\ (EP500 + EP507 +$

$EP501 + EP502 + EP503 + EP504 + EP505 + EP506) \times \Delta\tau$

TOTAL OPERATING ENERGY

SYSOPE = CSOPE + HOPE + COPE

AUXILIARY THERMAL ENERGY (BTU)

HAT = HEATING AUXILIARY THERMAL ENERGY

CAT = COOLING AUXILIARY THERMAL ENERGY

AUXILIARY FUEL CONSUMED

AFC = F500 x 1,000.0

COOLING AUXILIARY FOSSIL FUEL

CAF = [HLC/(HL + HLC)] x AFC

HEATING AUXILIARY FOSSIL FUEL

HAF = [(HL/(HL + HLC)] x AFC

TOTAL AUXILIARY THERMAL ENERGY

AXT = CAT + HAT

TOTAL AUXILIARY FOSSIL FUEL (BUT)

AXF = CAF + HAF

APPENDIX C

LONG-TERM AVERAGE WEATHER CONDITIONS

SITE: IRVINE SCHOOL 16. LOCATION: IRVINE CA

ANALYST: H. SMITH FDRIVE NO.: 66.

COLLECTOR TILT: 25.00 (DEGREES) COLLECTOR AZIMUTH: 0.0 (DEGREES)

LATITUDE: 33.73 (DEGREES) RUN DATE: 6/04/79

MONTH	HOBAR	HBAR	KBAR	RBAR	SBAR	HDD	CDD	TBAR
JAN	1660.	948.	0.57075	1.455	1379.	339	0	54.
FEB	2094.	1235.	0.58981	1.307	1615.	273	7	56.
MAR	2628.	1611.	0.61303	1.161	1870.	247	0	57.
APR	3150.	1928.	0.61225	1.030	1987.	146	16	61.
MAY	3489.	2072.	0.59394	0.947	1963.	71	43	64.
JUN	3616.	2194.	0.60665	0.912	2002.	23	92	67.
JUL	3545.	2363.	0.66674	0.925	2187.	0	226	72.
AUG	3273.	2157.	0.65907	0.994	2144.	0	263	73.
SEP	2811.	1737.	0.61778	1.106	1920.	7	211	72.
OCT	2247.	1357.	0.60395	1.258	1707.	48	107	67.
NOV	1760.	1025.	0.58254	1.417	1453.	155	23	61.
DEC	1537.	870.	0.56603	1.505	1309.	295	0	56.

LEGEND:

HOBAR ==> MONTHLY AVERAGE DAILY EXTRATERRESTRIAL RADIATION (IDEAL) IN BTU/DAY-FT2.

HBAR ==> MONTHLY AVERAGE DAILY RADIATION (ACTUAL) IN BTU/DAY-FT2.

KBAR ==> RATIO OF HBAR TO HOBAR.

RBAR ==> RATIO OF MONTHLY AVERAGE DAILY RADIATION ON TILTED SURFACE TO THAT ON A HORIZONTAL SURFACE FOR EACH MONTH (I.E., MULTIPLIER OBTAINED BY TILTING).

SBAR ==> MONTHLY AVERAGE DAILY RADIATION ON A TILTED SURFACE (I.E., RBAR * HBAR) IN BTU/DAY-FT2.

HDD ==> NUMBER OF HEATING DEGREE DAYS PER MONTH.

CDD ==> NUMBER OF COOLING DEGREE DAYS PER MONTH.

TBAR ==> AVERAGE AMBIENT TEMPERATURE IN DEGREES FAHRENHEIT.